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THESIS

SOLAR POWER STATIONS FOR REMOTE SITES: AN ECONOMIC ANALYSIS

Submitted by

Thomas C. Kocian

Mechanical Engineering

In partial fulfillment of the requirements

for the degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer, 1981

COLORADO STATE UNIVERSITY

Summer, 1981

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY Thomas C. Kocian

ENTITLED: SOLAR POWER STATIONS FOR REMOTE SITES: AN ECONOMIC ANALYSIS

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COMMITTEE ON GRADUATE WORK

S. Karaki

Paul J. Wilbur

C. Byron Winn

William A. Duff

Advisor

ABSTRACT OF THESIS

SOLAR POWER STATIONS FOR REMOTE SITES: AN ECONOMIC ANALYSIS

While solar power plants are not presently economically competitive with fossil fuel power plants at most locations, solar power may be competitive at some remote locations. Energy at remote locations is both costly and subject to disruptions due to hostilities and/or shortages of fuel. Even if the direct costs of fossil fuel power plants are not sufficient to make solar power economically attractive the costs associated with fuel supply disruptions (or the possibility of disruptions) may make solar power desirable. Evaluation of the economic and strategic feasibility of utilizing solar power can be accomplished by comparing the uniform annual costs of competing systems over thier lifetimes.

Formulas are developed for fossil fuel and solar power plants to enable economic evaluation of the costs of competing power plants. Evaluation can be accomplished whether the present power plant requires replacement, or if it is desired to reduce use of, and dependence on, fossil fuels even though the present power plant is still servicable. An example

shows that solar derived energy may be economically feasible, depending on the cost data and assumptions used for a study.

Thomas C. Kocian
Mechanical Engineering Department
Colorado State University
Fort Collins, CO 80523
Summer, 1981

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CHAPTER 1

INTRODUCTION

While solar power plants are not presently economically competitive with fossil fuel power plants at most locations, there are factors which enhance the economic feasibility of solar power plants (2). Some of these factors are:

a) Regions of high annual solar radiation.

b) Land availability at reasonable cost.

c) High cost of fossil fuels.

d) Maximum utilization of collected energy.

e) Efficient collection of solar energy.

f) Low lifecycle solar power plant costs.

Many remote military sites have the first four of these characteristics and therefore may be candidates for economically competitive solar power plants. The last two of the characteristics are primarily functions of plant design and are not directly attributable to the location of the power plant. Even if the direct costs of fossil fuels are not sufficient to make solar power plants economically attractive, it is possible that solar power may be desirable given factors that are not entirely determined by fuel costs.

This can be especially true at remote military sites where power is provided by small independent power plants. At remote military sites, the cost of power can be related to the dollar cost of providing fossil fuel derived power, plus the cost of loss of power due to fuel supply problems and the marginal costs of using scarce fuel. Fuel supply problems can result from embargos,

hostilities, and from denial of fuel supply delivery. In cases of fuel supply problems, there may be costs associated with the loss of, or reduction in, mission capabilities at a site. For example, if an air-defense radar site can not be kept supplied with fuel, it will cease to operate after available on-site fuel supplies are depleted. Loss of a ground based radar system may necessitate the use of an airborne radar system with it's higher operating costs. In this case, the cost of not having a fossil fuel supply independent power system could be the cost of operating the airborne system minus the costs of operating the ground-based system that are not incurred because fuel is not available.

The intent of this thesis is to provide a system for evaluating the economic feasibility of utilizing solar power to replace fossil fuel derived power. A comparison of the economic and strategic costs of providing fossil fuel derived and solar derived power will be used for this determination. The cost of fossil fuel power at a given location is used for comparison with costs of proposed solar power plants to provide a basis for decisions on implementing solar power plants. Fossil fuel power costs can be determined for varying probabilities of events (hostilities, embargos, etc.) occurring, and then comparing these costs to solar power plant option costs. Sensitivity analyses for the major cost determinants of both fossil fuel and solar power plants must be conducted to ensure that estimated values do not unduely bias the results of a comparison.

This thesis is not intended to determine the optimum solar power plant type or size for consideration. Additionally, alleged sociological and environmental advantages of solar power are outside the scope of this paper. It is designed to provide a method for determining the economic

feasibility of a solar power plant after the type and size of solar power plant have been optimized for a particular location. Given the costs associated with an optimized solar power plant, economic factors can be evaluated to determine the economic feasibility of providing solar power at the site for which the power plant was optimized. This paper is primarily oriented towards solar thermal and photovoltaic power systems; however, the results are applicable to other types of solar power with relatively minor modifications.

CHAPTER 2

METHODOLOGY OF ECONOMIC COMPARISON

For systems which are going to last for more than one year, it is necessary to compare system costs over system lifetimes. An appropriate approach is to use one of the available methods of comparing lifetime costs of competing alternatives.

2.1 ENGINEERING ECONOMICS

Engineering economics provides methods by which the costs of alternative methods of providing the same result can be compared. The concepts of time value of money and discounted cash flow are generally accepted for this purpose.

An interest rate is a measure of the productivity of capital in real terms. For the federal government, the time value of money can be considered in several ways. First, it may be considered to be zero, since most of the money comes from tax revenues which does not require borrowing directly from lending institutions. Second, the value of money could be considered to be that return on investment which the taxpayers could receive on the money if they did not have to pay it in taxes. Third, the time value of money could be considered the interest rate paid on government borrowing.

Cash flows have both a monetary value and a time value. In order to reduce cash flows at various times to equivalent cash flows at a fixed time, the

value of future cash flows may be reduced to the present by the time value of money, usually represented by i. A discount rate (d) is the minimum acceptable rate of return on an investment. The discount rate is usually higher than the cost of capital, or the interest rate, to compensate for risk and overhead costs. There are several basic factors which occur frequently in Engineering Economics. Therefore, it is convenient to calculate the value once at the outset to avoid unnecessary repetitions. These factors are:

a) Compound Amount Factor: (F/P,i,n)

b) Present Worth Factor: (P/F,i,n)

c) Sinking Fund Factor: (A/F,i,n)

d) Series Compound Amount Factor: (F/A,i,n)

e) Capital Recovery Factor: (A/P,i,n)

f) Series Present Worth Factor: (P/A,i,n)

g) Uniform Amount Gradient Factor: (A/G,i,n)

h) Present Worth Gradient Factor: (P/G,i,n)

The factors are presented in numerous publications (1,7) and are not contained herein.

In these factors, the future value is represented by F, the present value by P, a series of uniform periodic payments by A, a series of payments increasing or decreasing by a fixed amount each period is represented by G, the value of money by i, and the number of equal periods between payments or credits by n.

Cash flow factors can be used to reduce costs associated with the purchase and operation of a system into a series of uniform yearly payments, called uniform annual costs (UAC), over the expected economic or physical

lifetime of the system. Alternatively, the cost components could be accumulated into a sum representing the total present worth of all future cash flows. The UAC and present worth analyses will give the same results for a given system since the two are related by the capital recovery factor. Therefore, the UAC method will be used in this paper.

2.2 TYPES OF COSTS

Two basic types of costs can be identified in the economic analyses of fossil fuel and solar power plants. The first type are initial capital costs, and the second type are costs that recur throughout the system's life and includes such items as maintenance, operations, and fuel costs. The capital costs can easily be converted into uniform annual costs by the capital recovery factor. Annual costs must include the effects of differential inflation in the future costs of fuel, maintenance, etc. Inflation effects can be included by using modified compound interest factors.

For example, positive differential inflation applies to fuel costs in a period when fuel prices are increasing more rapidly than the general rate of inflation. The differential rate (e) is given by: e = rate of change of a specific cost factor. If the differential rate is e, the inflation modified discount rate factor is given by:

$$C_x = (X_o) \times (A/P,g,n)/(A/P,i',n)$$

C_x is the equivalent annualized cost, X_o is the cost in the first year, g is the general rate of inflation, and i' is the inflation modified discount rate, given by $i' = (g - e)/(1 + e)$.

This formula can be used to find the annualized cost of maintenance, operations, and other future annual costs if they increase at a rate other than the general rate of inflation. If a cost factor increases at the general inflation rate, then the modified discount rate is zero percent and the modified discount rate factor $(1/(A/P,i',n))$ is equal to $(n/(1 + g))$.

2.3 ASSUMPTIONS

Any analysis of future economic behavior requires that assumptions be made concerning future prices, events, and the time value of money. In the analysis contained herein, it is assumed that the time value of money, the rate of increase of cost factors, and the probabilities of events occurring are constant over the system lifetime. In addition, all factors not affected by inflation are assumed to be constant. For example, the cost of fuel used in a given year is a function of the number of units of fuel used, the price per unit, and the transportation and storage costs per unit. It is assumed that the number of units of fuel used will remain constant while the price, transportation and storage costs will increase at some rate, or rates, per unit of fuel used.

CHAPTER 3

UNIFORM ANNUAL COST OF A FOSSIL FUEL POWER PLANT

When consideration is being given to replacing an existing fossil fuel power plant with a solar power plant, one of two conditions exist. First, the present power plant is worn out and requires replacement with some form of power plant. Or, second, the present power plant has useful life remaining, but it is desirable to reduce the cost of or dependence on fossil fuels. Both of these conditions will be treated separately.

3.1 POWER PLANT REQUIRES REPLACEMENT

Given that the present power plant requires replacement, it is necessary to determine what type of power plant can provide the required energy most economically over the projected system lifetime. The UAC of a fossil fuel power plant will be primarily dependent on the time value of money, the rate of increase in the cost of fuel, fuel transportation, operations, and maintenance costs for the power plant, and changes in the marginal costs of providing security for fuel delivery, and the costs of fuel supply denial. Once the rates of change are determined for these factors, they can be used in a formula to calculate the UAC of a fossil fuel power plant, This formula is shown below:

$$UAC_F = (A/P,d_1,n) \times (C_{CI(P)} + C_{CI(A)}) + (A/P,g,n) \times (1/(A/P,i'_1,n)) \times C_F + (1/(A/P,i'_2,n)) \times C_{TF} + (1/(A/P,i'_3,n)) \times C_{O(P + A)} + (1/(A/P,i'_4,n)) \times C_{M(P + A)} + (1/(A/P,i'_5,n)) \times C_{AF} + (1/(A/P,i'_6,n)) \times E_{MC} + (1/(A/P,i'_7,n)) \times E_{MI} + (1/(A/P,i'_8,n)) \times E_S + (1/(A/P,i'_9,n)) \times E_{SD} - (A/F,d'_2,n)) \times SV$$

The discount factors were presented in Chapter 2. The cost factors, d's, and i's are defined below:

$C_{CI(P)}$ = Total capital and installation costs of the primary power plant ($).

$C_{CI(A)}$ = Total capital and installation costs of the auxiliary or backup power plant ($).

C_F = Direct costs of the fuel used by the power plants in year zero ($).

C_{TF} = Transportation and storage costs of the fossil fuel used by the power plants in year zero ($).

$C_{O(P+A)}$ = The costs of operating the primary and auxiliary power plants in year zero ($).

$C_{M(P+A)}$ = The costs of maintaining the primary and auxiliary power plants in year zero ($).

C_{AF} = The direct, transportation, and storage costs for any fuel required for energy needs not supplied by the power plants in year zero, where the energy need could be supplied by a solar power plant ($).

E_{MC} = Expected value of the marginal cost of using scarce fuel in year zero ($), as determined in Appendix A.

E_{MI} = Expected value of the mission impact costs of reduced or discontinued fuel supplies due to fuel shortages in year zero ($), as determined in Appendix A.

E_S = Expected value of the cost of providing security for fuel deliveries in year zero ($), as determined in Appendix A.

E_{SD} = Expected value of the cost of fuel supply denial in year zero ($), as determined in Appendix A.

SV = Salvage value of the power plants at the end of the plant lifetime ($).

d_1 = The discount rate or time value of money for the capital costs.

d_2 = The discount rate for the salvage value.

g = The general rate of inflation.

i'_1 = The modified discount rate for fuel costs.

i'_2 = The modified discount rate for fuel transportaion costs.

i'_3 = The modified discount rate for operating costs.

i'_4 = The modified discount rate for maintenance costs.

i'_5 = The modified discount rate for auxiliary fuel costs.

i'_6 = The modified discount rate for the marginal cost of fuel.

i'_7 = The modified discount rate for the mission impact cost of fuel.

i'_8 = The modified discount rate for the cost of fuel transportaion security.

i'_9 = The modified discount rate for the cost of fuel supply denial.

The equation assumes that the rate of change for each of the cost factors will be constant over the system lifetimes and that there is no change in the probabilities of events occurring which will affect the expected values. If the rate of change of a cost factor is not a constant, then the UAC for that cost factor must be divided into time segments where the rate of change is a constant.For example, if the cost of fuel (C_F) were expected to increase at a rate of 10% per year for five years and after that at a rate of 6% per year until the end of the system's lifetime, then the UAC for the cost of fuel would be

changed as shown below (with a general rate of inflation of 6% and a discount rate of 6% per year):

$$UAC_{C_F} = C_F \times (A/P,6,n) \times (1/(A/P,-3.6,5)) + C_F \times (F/P,10,5) \times ((A/P,6,n) - (A/P,6,5))$$

Where:

(A/P,6,n) = Discount rate factor for the time value of money.

(1/(A/P,-3.6,5) = Inflation modified discount rate factor for the first five years.

(F/P,10,5) = Compound amount factor to increase the present cost of fuel to the cost of fuel in five years.

(A/P,6,5) = Discount rate factor used to subtract the cost of fuel when the rate of change was 10% and not 6%.

A similar process is used if any of the cost factors do not change at a rate that is constant, or if any of the probabilities of events occurring are not constant.

If the UAC for a proposed power plant is less then the UAC for an alternative energy power plant, then it is economically attractive to install the proposed power plant under the conditions and assumptions used in the analysis. Prior to any decision, sensitivity analyses should be accomplished to determine the responsiveness of costs to changes in factors that have a major impact on the UACs for competing systems.

3.2 POWER PLANT DOES NOT REQUIRE REPLACEMENT

If the present power plant does not require replacement because it is not at the end of it's economic life, then the problem is not whether to

replace it with another fossil fuel plant or an alternative energy power plant. Instead, it must be determined if it is economically feasible to replace the existing, servicable power plant with an alternative energy power plant in order to reduce the use of fossil fuels. This type of economic analysis is generally accomplished through a replacement study.

A replacement study is used to determine if it is more economical to continue using an existing asset, or if the asset should be replaced by a competing asset. In this case, the concern is if an existing fossil fuel power plant can be economically replaced by a solar power plant. The UAC of a proposed solar power plant is compared to the UAC of the existing power plant, for it's most economical lifetime (where the UAC is lowest). The UAC for the replacement of an existing power plant can be determined by:

$$UAC_R = (A/P,g,n) \times ((1/(A/P,i'_1,n)) \times C_F + (1/(A/P,i'_2,n)) \times C_{TF} + (1/(A/P,i'_3,n)) \times C_{O(P+A)} + (1/(A/P,i'_4,n)) \times C_{M(P+A)} + (1/(A/P,i'_5,n)) \times C_{AF} + (1/(A/P,i'_6,n)) \times E_{MC} + (1/(A/P,i'_7,n)) \times E_{MI} + (1/(A/P,i'_8,n)) \times E_S + (1/(A/P,i'_9,n)) \times E_{SD} + (A/P,d,n) \times (\text{Present salvage value}) - (A/F,d,n) \times (\text{Salvage value at the most economical lifetime})$$

Where: n is the number of years to the most economical lifetime. Salvage values are included if the value of the asset minus the cost to remove and transport the asset to another location is greater than zero.

If the UAC of a proposed solar power plant over it's lifetime is less than the UAC of the existing power plant over it's most economical lifetime, then it is economically attractive to replace the existing power plant with the proposed solar power plant. If the UAC of a proposed solar power plant is greater than the UAC of the existing power plant over it's most economical lifetime, replacement is not economically justified at the time of the study. Since costs

will generally increase with system age, it may be economical at some future time prior to the end of the economical life and additional replacement studies can be accomplished. Prior to any decision, sensitivity analyses should be accomplished to determine the responsiveness to changes in factors which have a major impact on the UAC for both competing systems.

CHAPTER 4

UNIFORM ANNUAL COSTS OF A SOLAR POWER PLANT

The UAC of a solar power plant will be primarily dependent on the time value of money, the first costs of the system, the amount of nonsolar energy required, and the operating and maintenance costs of the system. An equation for calculating the UAC of a solar power plant is:

$$UAC_{SP} = (A/P,d_1,n) \times (C_G + C_E + C_{NS}) + (A/P,g,n) \times ((1/(A/P,i'_{10},n)) \times C_{O(SP + NS)} + (1/(A/P,i'_{11},n)) \times C_{M(SP + NS)} + (1/(A/P,i'_1,n)) \times C_F + (1/(A/P,i'_2,n)) \times C_{TF} + (1/(A/P,i'_5,n)) \times C_{AF} + (1/(A/P,i'_6,n)) \times E_{MC} + (1/(A/P,i'_7,n)) \times E_{MI} + (1/(A/P,i'_8,n)) \times E_S + (1/(A/P,i'_9,n)) \times E_{SD} - (1/(A/P,i'_{12},n)) \times C_R + (A/F,d_2,n)) \times SV$$

The discount factors were presented in Chapter 2. The cost factors and discount rates not defined in Chapter 3 are:

C_G = Total capital costs of purchasing and installing the solar power plant (except storage) (\$).

C_E = Total capital costs of purchasing and installing the storage portion of the solar power plant (\$).

C_{NS} = Total capital costs of purchasing and installing the nonsolar backup or auxiliary power plant (\$).

$C_{O(SP + NS)}$ = Total costs of operating the solar and nonsolar power plants in year zero (\$).

$C_{M(SP + NS)}$ = Total costs of maintaining the solar and nonsolar power plants in year zero ($).

C_F = Direct costs of fossil fuel used by the auxiliary power plant in year zero ($).

C_R = Cost reductions realized by using solar power and not accounted for elsewhere, in year zero ($).

i'_{10} = The modified discount rate for the operating costs of the solar and nonsolar power plants.

i'_{11} = The modified discount rate for the maintaining costs of the solar and nonsolar power plants.

i'_{12} = The modified discount rate for the cost reductions not accounted for elsewhere.

The equation assumes the rate of change of each of the cost factors will be constant over the system lifetimes, and that there is no change in the probabilities of events occurring which affect the expected values. If any of the rates of change or probabilities of events are not constant, then the cost can be treated as discussed in Chapter 3.

If the UAC for an evaluated solar power plant is less than the UAC for a competing fossil fuel power plant, then under the assumptions and conditions used, it is economically attractive to use the solar power plant. Prior to any decision, sensitivity analyses should be accomplished to determine the responsiveness of costs to changes in factors that have a major impact on the UACs for competing systems.

CHAPTER 5

EXAMPLE

This is an illustrative example designed to show how to apply the methodology developed, and is not intended to evaluate the economic feasibility of a particular system at the selected location. The results shown are, of course, dependent on the values used for subsystem performance and costs, as well as the probabilities of events occurring. The values used are not intended to represent an optimized solar power system evaluated under a specific scenario, but are intended to be representative of available data. Evaluations over ranges of critical parameters are accomplished to illustrate sensitivity analyses. Assumptions are stated as they are made.

The source of the research topic, U.S. Air Force Systems Command, Electronics Systems Division, has identified Ascension Auxiliary Airfield (AAF), Ascension Island as a representative remote site for the consideration of solar power (13). Ascension Island is a British Island located in the South Atlantic at latitude 8^{o} 0' South, longitude 14^{o} 15' West. The Air Force installation is located on 3,856 acres occupied under agreement with England.

5.1 FOSSIL FUEL POWER PLANT

In response to requests, the commander of Ascension AAF (Lt Col Donovan) has provided the following information which may be used to calculate the cost of utilizing fossil fuel derived energy. Table 1 contains the consumption data for three months of operation and the average monthly use

Table 1 Consumption Data From Ascension AAF

Item	April, 1980	May, 1980	June, 1980	Monthly Average
Water (gal)	993,321	1,032,485	942,748	989,518
Electricity (KWh)	1,296,960	1,421,000	1,266,840	1,328,267
Aircraft Fuel (gal)	348,615	399,410	278,969	342,331
MOGAS (gal)	5,242	4,516	3,977	4,578
Diesel (gal)	132,999	157,651	136,823	142,491

for the three months. It is assumed that the figures are representative of year around usage. The base is supplied with JP-5 (diesel and aircraft fuel) and MOGAS (automotive fuel) on a regular basis three to four times a year by ship. Fuel ships average five to seven day, trip-chargeable transit times to the site, plus one day to offload, at a rate of $22,413 per ship-day. Fuel is offloaded by floating hose to the POL farm where it is stored. From the POL farm, fuel is trucked to the airfield and the various sites as needed.

Base power production is centrally located, however, each critical site has standby generating capabilities. The main power plant has a generating capacity of 5300KW, with this capacity provided by 14 diesel-powered generators. Backup generating capacity is 3700KW provided by diesel-powered generators at the various sites.

Energy denial of JP-5 would seriously affect capability to support any contingency of aircraft which may require staging through Ascension. The primary station mission of missle and space object tracking could be degraded before it would have to be stopped.

Strategic use for airlift could develop as the primary mission during hostilities. The cost of JP-5 was $1.32/gal and MOGAS cost $1.26/gal in July, 1980. The site has a 1,005 MB (1.005 x 10^6 BTU/hr) steam boiler to provide hot water for the site. The assumptions of constant time value of money, rates of increase of cost factors, and probabilities of events as detailed in Chapter 3 apply in this example. The following assumptions also apply:

(a) The year zero costs for JP-5, MOGAS, and fuel transportation to the site will be those supplied for July 1980 by the site.

(b) Diesel fuel is consumed at a rate equal to the three month average consumption rate of 142,491 gal/mo and provides all electrical, heating, cooling needs (e.g. $C_{AF} = 0$).

(c) The base will be supplied with fuel an average of 3.5 times per year, with an average chargeable time of seven days per trip (includes one day for offloading) at a rate of $22,413 per ship-day.

(d) The cost to purchase, transport, install, and test replacement diesel-powered generators is assumed to be $375/KW of capacity (Source 11 with modifications for inflation since 1976).

(e) Backup or auxiliary generating capacity is available on the base and will not require replacement during the system lifetime ($C_{CI(A)} = 0$).

(f) It is assumed that 3000KW of generating capacity for the primary power plant requires replacement, also, the efficiency of replacement diesel-powered generators will be the same as the present generators.

(g) Cost of transporting fuel by truck on the base and the cost of storage of the fuel at the site is assumed to be $0.01/gal ($0.008/gal transportation and $0.002/gal storage).

(h) The cost of operating the primary and auxiliary power plants is 1% of the capital value ($375/KW) for year zero. The costs of maintaining the primary and auxiliary power plants are also 1% of the capital value for year zero (8).

(i) The marginal cost of using fuel in short supply is \$0.05/gal. $P(E) = 0.10$, $P(T_e|E) = 0.20$, and $P(D_e|E \cap T_e) = 0.75$.

(j) The marginal impact cost of less than full delivery of fuel to the base is \$1,000,000/year.

(k) Security for fuel delivery, if required, is assumed to be a destroyer escort at twice the cost of fuel transportation. $P(H) = 0.01$, $P(T_h|H) = 0.30$, and $P(D_s|H \cap T_h) = 0.50$, and $P(SD|H \cap T_h) = 0.75$.

(l) The cost of fuel supply denial is the cost of the loss of the primary mission capabilities, assumed to be the same as the marginal impact cost of less than full delivery of fuel supplies.

(m) The discount rate (d_1) is assumed to be 5%, the rates of increase for the cost factors are assumed to be: 6% for e_1 and e_5; 5% for e_2, e_3, e_4, e_7, and e_{10}; and 7% for e_6, e_8, and e_9. The general rate of inflation (g) is 6% and the system lifetime is 25 years.

(n) The cost of removing and transporting generators is assumed to be greater than the salvage value of the generators, therefore, the generators will have zero salvage value.

Given these assumptions, the uniform annual cost of the fossil fuel derived power can be determined from the equation developed in Chapter 3 for a power plant requiring replacement:

$$UAC_C = = (A/P,d_1,n) \times (C_{CI(P)} + C_{CI(A)}) + (A/P,g,n) \times ((1/(A/P,i'_1,n)) \times C_F + (1/(A/P,i'_2,n)) \times C_{TF} + (1/(A/P,i'_3,n)) \times C_{O(P+A)} + (1/(A/P,i'_4,n)) \times C_{M(P+A)} + (1/(A/P,i'_5,n)) \times C_{AF} + (1/(A/P,i'_6,n)) \times$$

$E_{MC} + (1/(A/P,i'_7,n)) \times E_{MI} + (1/(A/P,i'_8,n)) \times E_S + (1/(A/P,i'_9,n)) \times E_{SD} - (A/F,d_2,n)) \times SV$

Where:

$C_{CI(P)}$ = (3000KW) x ($375/KW) = $1,125,000.00.

$C_{CI(A)}$ = $0.00.

C_F = ($1.32/gal) x (142,491 gal/mo) x (12 mo/yr) = $2.257,057.00/yr.

C_{TF} = Total fuel transportation costs by ship times the fraction of delivered fuel used for solar replaceable energy, plus site transportation and storage costs.

$= ((3.5 \text{ trips/yr}) \times (7 \text{ ship-days/trip}) \times (\frac{142{,}491}{142{,}491 + 342{,}331 + 4{,}578}) \times (\$22{,}413/\text{ship-day}) + ((\$0.01/\text{gal}) \times (142{,}491 \text{ gal/mo}) \times (12 \text{ mo/yr}))$

= $176,977.00/yr.

$C_{O(P + A)}$ = (($375/KW) x (5300KW primary + 3700KW backup) x (0.01)) = $33,750.00/yr.

$C_{M(P + A)} = C_{O(P + A)}$ = $33,750.00/yr.

C_{AF} = $0.00.

$E_{MC} = P(E) \times P(T_e|E) \times P(D_e|E \cap T_e) \times C_{MC}$

= (0.10) x (0.20) x 0.75) x (($0.05/gal) x (1,709,892 gal/yr)) = $1,282.00/yr.

$E_{MI} = P(E) \times P(T_e|E) \times (1 - P(D_e|E \cap T_e) \times C_{MI}$

= (0.10) x (0.20) x (1 - .75) x (1,000,000.00) = $5,000.00/yr.

$E_S = P(H) \times P(T_h|H) \times P(D_s|H \cap T_h) \times C_S$ x (Percent of total fuel use , used for solar replaceable energy) = (0.01) x (0.30) x (0.50) x (($44,825.00/ship-day) x (3.5 deliveries/yr)) x (0.29) = $478.00/yr.

$E_{SD} = P(H) \times P(T_h|H) \times P(SD|H \cap T_h) \times C_{SD}$ = (0.01) x (0.30) x (0.75) x ($1,000,000.00/yr) x (3.5 deliveries/yr)) = $2,250.00/yr.

$SV = \$0.00.$

$d_1 = 5\%$ $d_2 = 5\%$ $i'_1 = -0.94\%$

$i'_2 = 0\%$ $i'_3 = 0\%$ $i'_4 = 0\%$

$i'_5 = -0.94\%$ $i'_6 = -1.9\%$ $i'_7 = 0\%$

$i'_8 = -1.9\%$ $i'_9 = -1.9\%$ $n = 25$ years

Therefore:

$$UAC_C = (0.07095) \times (\$1,125,000) + (0.07095) \times ((28.345) \times (\$2,257,057) + (23.810) \times (\$176,977) + (23.810) \times (\$33,750) + (23.810) \times (\$33,750) + (32.246) \times (\$1,282) + (23.810) \times (\$5,000) + (32.246) \times (\$478) + (32.246) \times (\$2,250) = \$5,058,745.00/yr.$$

The UAC for diesel-powered generators with 3 MW of the present generating capacity replaced is approximately \$5.1 million, given the assumptions made.

5.2 SOLAR POWER PLANT

Source 9 indicates that a distributed dish collector system is more cost effective than other solar power plant designs, up to 10 MW_e of capacity. This parabolic dish system includes a small heat engine (Stirling)/generator coupled directly to the receiver and mounted at the focal point of the dish. The system generates electricity at the distributed dishes, therefore energy storage is in the form of electricity via mechanical, chemical, or electromagnetic means. Advanced battery storage is used in this example.

It is assumed that the thermal requirements of the site will be met by the stored energy form, low temperture heat removed for the distributed

dishes and retained in low temperature storage, or through separate low temperature collectors and storage. Thermal requirements include domestic hot water, space heating, water desalinization, etc. Since thermal requirements are not addressed in the source, a cost factor decrease of 10% will be used. The Stirling dish-electric system has nearly constant performance and costs over a wide range of sizes due to the inherent modularity of the system. Figure 1 shows the cost variation with respect to system size for several system types. For example, it is assumed that a 3 MW_e solar power plant with an annual capacity factor of 0.75 will best meet the site's requirements. Figure 2 shows the required area of concentrator field vs the annual capacity factor for various storage capacities (9) using advanced battery storage. The original graph was based on a plant capacity of 100 MW_e. Since the Stirling dish-electric system is modular, adjustment of collector area for capacity differences is a direct proportional adjustment. Therefore, the collector area in Figure 2 was proportionally adjusted from a capacity of 100 MW_e to a capacity of 10 MW_e.

The origin of the information in Figure 2 was also based on a power plant location in Inyokern, CA (35.65^o N. latitude). Since the location of interest is Ascension Island (8^o S. latitude), the collector area in Figure 2 needs to be adjusted for insolation differences between the two sites. The effects of factors other than latitude on insolation at the sites are assumed to be equal for the two sites. These factors include weather differences, air pollution differences, relative humidity differences, etc. Since actual surface insolation are not available for Ascension Island, a comparison between the monthly average daily extraterrestial radiation for the two locations was accomplished (12). The monthly average daily and yearly average daily extraterrestial radiation for the two locations are contained in Table 2.

Figure 1 Effect of Plant Size on
Energy Costs

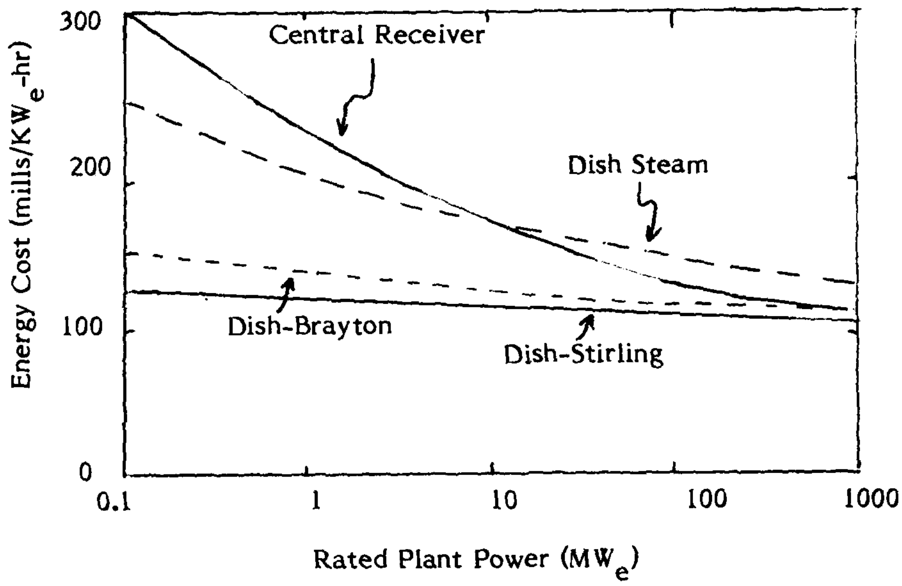


Figure 2. Parabolic Dish-Electric
Plant Performance (10 MW_e)

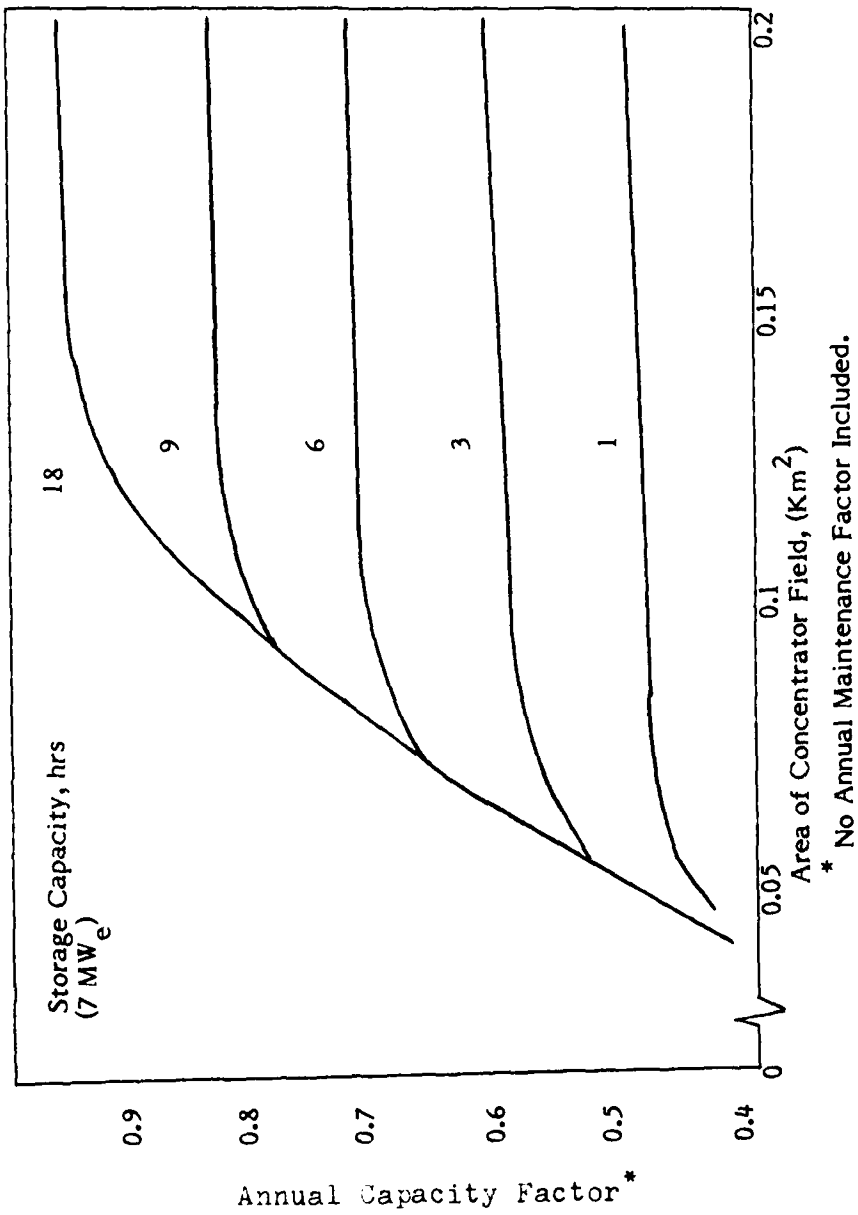


Table 2 Average Daily Extraterrestial Radiation, MJ/m^2

Site	Average Daily Extraterrestial Radiation												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Inyokern	17.7	22.5	29.0	35.4	39.5	41.1	40.2	36.8	31.1	24.4	18.8	16.3	24.6
Ascension	38.5	38.6	37.4	34.7	31.5	29.8	30.4	34.6	36.6	37.4	36.9	36.5	35.2

NOTE: For $G_{SC} = 1353\ W/m^2$.

From the data in Table 2, it can be determined that the average daily extraterrestial radiation at Ascension Island is 43% greater than at Inyokern for a standard year. Given the assumptions made, the average daily beam radiation at the surface should also be approximately 43% greater at Ascension than at Inyokern. In order to error on the side of conservatism, it will be assumed that beam radiation is 35% greater at Ascension than at Inyokern. Since more radiation is available per unit area at Ascension on the average, the amount of collector area required per MW_e of plant capacity will decrease. It will be assumed that the required collector area at Ascension will decrease by 35% for a given plant capacity. The result of this adjustment could be more conservative than indicated earlier. This possibility results from the fact that the insolation rate for Ascension is more constant throughout the year then is the rate at Inyokern. The maximum monthly difference for Inyokern from Table 2 are 24.8 MJ/m^2 and only 9.0 MJ/m^2 for Ascension. Therefore, plant capacity can be more effectively utilized at Ascension than at Inyokern. If the plant capacities are designed for the yearly average daily radiation rate, then a system at Inyokern could have from 16.5 MJ/m^2 of excess radiation to 8.3 MJ/m^2 of insolation less than capacity. The plant would be discarding a significant amount of energy (up to 67% of capacity) some of the time and operating at up to 34% below capacity at other times. On the other hand, a plant designed for Ascension's yearly average daily radiation rate would have only up to 3.4 MJ/m^2 (10% of capacity) of excess insolation and up to 5.4 MJ/m^2 (15%) less than capacity.

Costs given in the source article are for a startup in year 2000 with the year 2000 costs equal to 1.22 times the 1975 startup costs (in constant

1975 dollars) It will be assumed that 1980 costs (in 1975 dollars) will be 1.1 times the 1975 start up costs. These 1975 constant dollars will then be adjusted to 1980 dollars at a constant rate of inflation of 7% per year. Costs given (in 1975 dollars) for $10MW_e$ systems of the Stirling dish-electric type, and for three other types included in the source are contained in Table 3.

Adjusting the dish Stirling costs (Table 3) to the cost per m^2 of collector area for an annual capacity factor of 0.55 (with 13.6% downtime for annual maintenance, yields an annual capacity factor of 64% for Figure 2) results in the costs shown in Table 4 for a collector area of 0.07 Km^2 (70,000 m^2) for a 10 MW_e system. In addition, the costs are converted to 1975 startup costs (year 2000 startup costs divided by 1.22) and then these costs are converted into 1980 startup costs in constant 1975 dollars (1975 startup costs times 1.1). The 1980 startup costs are then converted to 1980 dollars (1975 dollars times $(1.07)^5$). In addition, since thermal energy needs such as hot water and water desalinization are not discussed in the source of the cost data, cost factors are increased by 10% to account for additional facilities, parts, etc. which may be needed.

Given the cost data in Table 4 for a 10 MW_e system, the cost factors need to be converted into costs for a 3 MW_e system at Ascension with a 75% capacity factor. From Figure 2, a 10 MW_e plant with a capacity factor of 75% (87% without maintenance time) requires a collector area of 0.11 Km^2. From Figure 1, a 3 MW_e power plant costs approximately 10% more than a 10 MW_e power plant in terms of energy costs (mills/KWh_e). The cost increase is primarily due to fixed costs constituting a larger fraction of plant costs when plant sizes are small. To accommodate this increase in costs, each cost factor for the 3 MW_e power plant is increased by 10%. It is assumed that a 3 MW_e

Table 3 Capital Cost Breakdown, Annual Capacity Factor = 0.55.

Item	System Type			
	Dish Stirling	Dish Steam	I-Axis Slats	Central Receiver
Direct Capital, $\$ \times 10^6$				
Collectors	14.0 (1)	21.0 (1)	20.5 (1)	20.0 (2)
Transport	0.5	3.0	1.5	3.0 (3)
Conversion	2.0	3.5	3.5	3.5
Storage	1.0	2.5	2.5	2.5
Other Capital (4), $\$ \times 10^6$	5.5	9.0	9.0	9.5
Total Capital, $\$ \times 10^6$	23.0	39.0	37.0	38.5

(1) Includes Receiver
(2) Heliostats Only
(3) Includes Tower, Receiver, and Transport
(4) Indirect, Spares, and Contingency
NOTE: Year 2000 Startup Costs

Table 4 Capital Cost Breakdown for Stirling Dish-electric Systems

Item	Startup Year/Reference Dollars				Add 10% for Thermal Power
	2000/ 1975	1975/ 1975	1980/ 1975	1980/ 1980	
Direct Capital, $\$/m^2$					
Collectors	200.0	163.9	180.3	252.9	278.2
Transport	7.1	5.8	6.4	9.0	9.9
Conversion	28.6	23.4	25.8	36.2	39.8
Storage	14.3	11.7	12.9	18.1	19.9
Other Capital, $\$/m^2$	78.6	64.4	70.9	99.4	109.3
Total Capital, $\$/m^2$	328.6	269.2	296.3	415.6	457.1
Operations and Maintenance, $\$/m^2$-yr. (First year of operation)	5.3	4.3	4.8	6.7	7.4

power plant will only require 30% of the collector area that a 10 MW_e power plant requires. Therefore, the collector area for the 3 MW_e power plant (insolation at Inyokern) is 33,000 m^2. It is assumed that all total costs except the collector costs will remain the same when collector area is reduced for Ascension's higher insolation rate. Therefore, all costs except collector costs will be based on 33,000 m^2 of collector area while collector costs will be based on 24,400 m^2 of collector area (33,000/1.35).

The results of these adjustments are given in Table 5. The cost data for the Inyokern solar power plants are assumed to include capital costs, transportation costs to the site, and installation and testing costs. However, transportation and installation costs at Ascension will probably be higher than the same cost factors at Inyokern since the transportation distance is much greater and all equipment and personnel will have to be transported to Ascension by ship or airplane. Therefore, the capital costs will be increased by an additional 10% for higher transportation and installation costs. Operation and maintenance costs are assumed to remain the same.

The assumptions of constant time value of money, rates of increase of cost factors, and probabilities of events occurring, used for the conventional power plant analysis also apply here. Additional assumptions made are:

(1) The cost per unit of fuel, fuel transportation and fuel storage assumed in the fossil fuel power plant analysis will also be used here for required fossil fuels.

(2) The amount of fossil fuel required to generate energy is assumed to average 25% of the amount used for fossil fuel only power. (0.25) x (142,491 gal/mo) x (12 mo/yr) = 427,473 gal/yr.

Table 5 Capital Costs of a 3 MW_e Power Plant

Item	3 MW_e at Inyokern	3 MW_e at Ascension	Adjustment for higher Transportation Costs
Direct Capital, $/m^2			
Collectors	9.18	6.79	7.47
Transport	0.33	0.33	0.36
Conversion	1.31	1.31	1.44
Storage	0.66	0.66	0.73
Other Capital, $/m^2	3.61	3.61	3.97
Total Capital, $/m^2	15.09	12.70	13.96
Operations and Maintenance, $/m^2-yr. (First year of operation)	0.24	0.24	0.24

(3) The cost of transporting and storing fuel used for power generation is ((0.09) x (3 deliveries/yr) x (7 ship-days/delivery) x ($22,413/ship-day) + ($0.01/gal) x (427,473 gal/yr) = $46,635/yr. Where, required deliveries decrease to three per year and the percentage of fuel used for power generation is 9% of total fuel deliveries.

(4) Backup or auxiliary generating capacity is available on the base and will not require replacement during the system lifetime ($C_{CI(A)}=0$). The auxiliary or backup power capacity is assumed to be 5 MW_e.

(5) The cost of operating and maintaining the fossil fuel power system are each assumed to be 1% of the capital value ($375/KW) for year zero. (0.01) x (5000 KW) x ($375/KW) = $18,500.00/yr. The costs of operating and maintaining the solar power plant are each $120,000.00/yr in year zero.

(6) The marginal cost of using fuel in short supply is $0.05/gal or (427,473 gal/yr) x ($0.05/gal) = $21,370.00/yr. $P(E) = 0.10$, $P(T_e|E) = 0.05$, and $P(D_e|E \cap T_e) = 0.40$.

(7) The marginal impact cost of less than full delivery of fuel to the base is $250,000/yr.

(8) Security for fuel delivery, if required, is assumed to be a destroyer escort at twice the cost of fuel transportation. (0.09) x (3 trips/yr) x (7 ship-days/trip) x ($44,826/ship-day) = $84,721.00/yr. $P(H) = 0.10$, $P(T_h|H) = 0.10$, and $P(D_s|H \cap T_h) = 0.90$. The cost of fuel supply denial is assumed to be the same as the marginal impact cost of less than full delivery of fuel ($250,000.00/yr).

(9) The time value of money, and the rates of increase in costs assumed for the fossil fuel power plant are used for the auxiliary or backup power plants.

(10) No cost reductions (C_R) except those accounted for in reduced utilization of fossil fuels are realized.

(11) Other rates of increase in costs are: i_{10} = 5%, i_{11} = 5%, and i_{12} = 5%. The system lifetime is 25 years.

Given these assumptions, the uniform annual cost of using solar power with nonsolar auxiliary power providing 25% of annual demand can be determined by the equation developed for solar power:

$UAC_{SP\#1} = (A/P,d_1,n) \times (C_G + C_E + C_{NS}) + (A/P,g,n) \times ((1/(A/P,i'_{10},n)) \times C_{O(SP + NS)} + (1/(A/P,i'_{11},n)) \times C_{M(SP + NS)} + (1/(A/P,i'_1,n)) \times C_F + (1/(A/P,i'_2,n)) \times C_{TF} + .(1/(A/P,i'_5,n)) \times C_{AF} + (1/(A/P,i'_6,n)) \times E_{MC} + (1/(A/P,i'_7,n)) \times E_{MI} + (1/(A/P,i'_8,n)) \times E_S + (1/(A/P,i'_9,n)) \times E_{SD} - (1/(A/P,i'_2,n)) \times C_R) + (A/F,d_2,n)) \times SV$

Where:

C_G = Total capital costs of purchasing and installing the solar power plant (except storage) = \$13.23 x 10^6.

C_E = Total capital costs of purchasing and installing the storage portion of the solar power plant = \$730,000.00.

C_{NS} = Total capital costs of purchasing and installing the nonsolar backup or auxiliary power plant = \$0.00.

$C_{O(SP + NS)}$ = Total costs of operating the solar and nonsolar power plants in year zero = (\$120,000.00 + 18,500.00) = \$138,500.00/yr.

$C_{M(SP + NS)}$ power plants in year zero =(\$120,000.00 + 18,500.00) = \$138,500.00/yr.

C_F = Direct costs of fossil fuel used by the auxiliary power plant in year zero = (427,473 gal/yr) x ($1.32/gal) = $564,264.00/yr.

C_{TF} = Transportation and storage costs of the fossil fuel used by the power plants in year zero ($).

C_{AF} = The direct, transportation, and storage costs for any fuel required for energy needs not supplied by the power plants in year zero, where the energy need could be supplied by a solar power plant ($).

E_{MC} = Expected value of the marginal cost of using scarce fuel in year zero ($), as determined in Appendix A.

E_{MI} = Expected value of the mission impact costs of reduced or discontinued fuel supplies due to fuel shortages in year zero ($), as determined in Appendix A.

E_S = Expected value of the cost of providing security for fuel deliveries in year zero ($), as determined in Appendix A.

E_{SD} = Expected value of the cost of fuel supply denial in year zero ($), as determined in Appendix A.

C_R = Cost reductions realized by using solar power and not accounted for elsewhere, in year zero ($).

$d_1 = 5\%$	$d_2 = 5\%$	$i'_1 = -0.94\%$
$i'_2 = 0\%$	$i'_3 = 0\%$	$i'_4 = 0\%$
$i'_5 = -0.94\%$	$i'_6 = -1.9\%$	$i'_7 = 0\%$
$i'_8 = -1.9\%$	$i'_9 = -1.9\%$	$n = 25$ years

Therefore:

$UAC_{SP\#1}$ = (0.07095) x (\$13,230,000 + 730,000) + (0.07095) x ((23.810) x (\$138,000) + (23.810) x (\$138,000) + (28.345) x (\$564,264) + (23.810) x (\$46,635) + (32.246) x (\$43) + (23.810) x (\$750) + (32.246) x (\$85) + (32.246) x (\$2,250) = \$2,678,671.00/yr.

The UAC for the solar power plant in this example with a fossil fuel auxiliary power plant is approximately $2.7 million, given the assumptions made. The solar power plant costs used in the preceeding example are for a system start date of 1990 or later and therefore assumes reductions in the costs of collectors, receivers, storage, etc. Other studies (14,15) indicate that these cost reductions may be extremely difficult to realize and that capital costs of a solar power plant will be much higher than the costs used in the previous example. Using cost data from sources 14 and 15, costs for a 3 MW_e solar power plant are shown in Table 6. If all cost factors of the previous example ($UAC_{SP\#1}$) except for solar power plant capital, operations and maintenance costs are assumed to remain the same, then the solar power plant $UAC_{SP\#2}$ would be $5.8 million.

5.3 COST ANALYSES

For the assumptions made, the first solar power plant described appears to be economically competitive. The second solar power plant UAC is greater than the fossil fuel power plant UAC as given. Further analyses of the responsiveness of major cost factors to changes in the cost factors, to changes in the rate of change of the cost factors, or to a change in the general rate of inflation are shown in the following paragraphs. Table 7 shows the amount which each of the cost factors contributed to the total UAC for each of the

Table 6 Capital Costs, Solar Power Plant Two

Item	1980 Costs	Thermal Power (+10%)	Transportation Costs Adjustment (+10%)
Direct Capital, ($\$ \times 10^6$)			
Collectors	22.74	25.02	27.52
Transport	1.25	1.38	1.52
Conversion	2.26	2.29	2.53
Storage	7.02	7.72	8.49
Other Capital, ($\$ \times 10^6$)	11.65	12.81	14.09
Total Capital, ($\$ \times 10^6$)	44.92	51.22	54.15
Operations and Maintenance, $\$ \times 10^6$/yr. (First year of operation)	0.41	0.41	0.41

Table 7 Cost Factor Contributions

Fossil Fuel	Solar Power # 1	Solar Power # 2
C_F = \$4,539,117.00	C_G = \$938,669.00	C_G = \$3,239,577.00
C_{TF}=\$ 313,913.00	C_F = \$628,062.00	C_O = \$ 692,621.00
C_{CI}= \$ 79,819.00	C_O = \$138,000.00	C_M = \$ 692,621.00
C_O = \$ 59,864.00	C_M = \$138,000.00	C_F = \$ 628,062.00
C_M = \$ 59,864.00	C_S = \$ 51,794.00	C_S = \$ 602,366.00
E_{MI}= \$ 8,869.00	C_{TF}=\$ 46,635.00	C_{TF}=\$ 46,635.00
E_{SD}= \$ 5,148.00	E_{SD}= \$ 2,798.00	E_{SD}= \$ 2,798.00
E_{MC}=\$ 2,933.00	E_{MI}= \$ 750.00	E_{MI}= \$ 750.00
E_S = \$ 1,094.00	E_S = \$ 106.00	E_S = \$ 106.00
	E_{MC}=\$ 54.00	E_{MC}=\$ 54.00

systems, given the assumptions made. As can be seen from Table 6 for the fossil fuel power plant, the cost of fuel is the primary factor affecting the UAC. The major cost factors affecting the UACs for the solar power plants are capital costs of the power plant, cost of fossil fuels, and operating and maintenance costs. The cost of storage is also significant for solar power plant two. The effects of these cost factors also depend on the general rate of inflation, the discount rate, and the rates of change of the cost factors. Therefore, the effects of variations in these factors were analyzed to determine the responsiveness of the UACs to changes.

If the discount rate remains at 5% and the general rate of inflation is varied from 0% to 10%, the results are as shown in Figure 3. If all other things remain the same, a lower general rate of inflation favors a solar power plant with it's lower annual costs, while a higher general rate of inflation makes a fossil fuel power plant with it's lower initial costs more competitive.

Since the cost of fossil fuel is a major factor in the UAC for both types of power plants, the responsiveness of the UAC's to changes in the rate of increase in the cost of fuel is shown in Figure 4. Since the present cost of fuel is well known, there is no reason to check the response to present fuel cost variations. All factors used in the original analysis except the rate of change for the cost of fuel remain the same for Figure 4. As expected, a low rate of increase for the cost of fuel favors fossil fuel power plants more than solar power plants, while a high rate of increase drastically increases the UAC for a fossil fuel power plant and has a much smaller affect on the UACs of the solar power plants.

Figure 3 Effects of the General Rate of Inflation

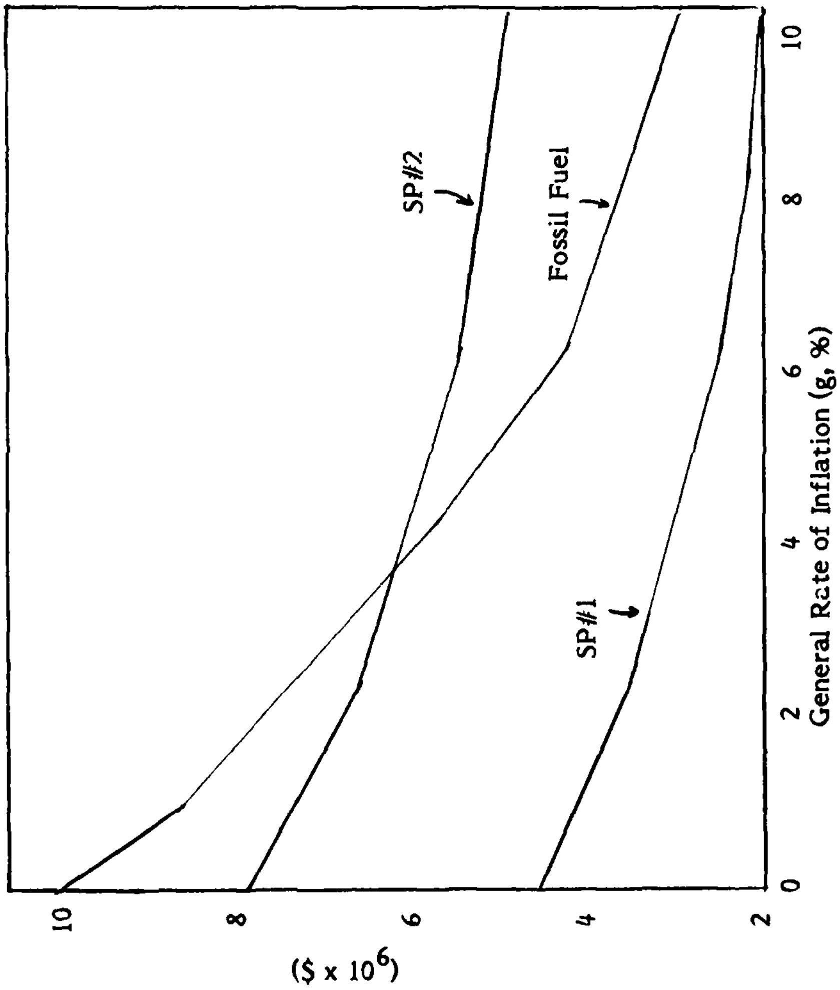
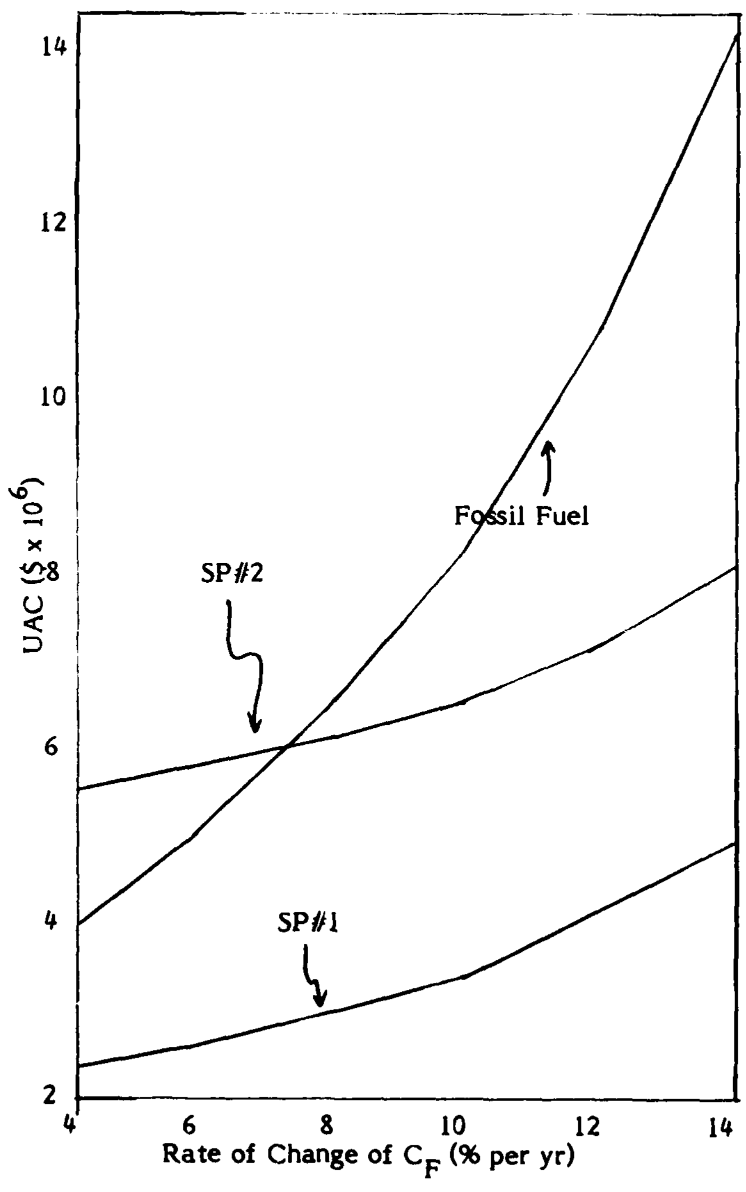
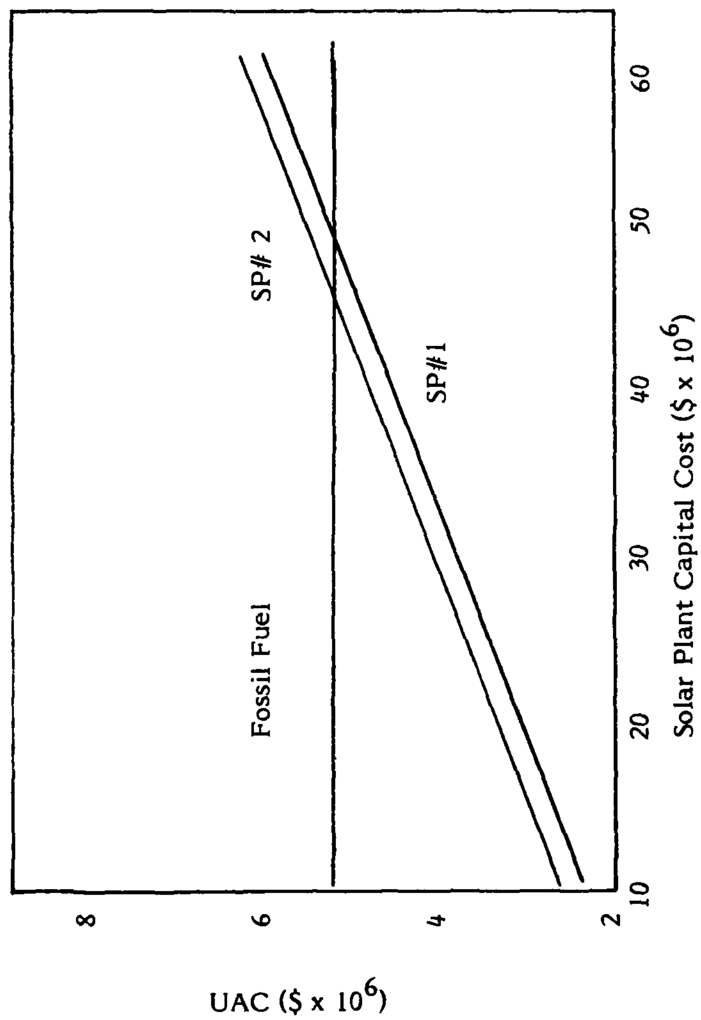


Figure 4 Effects of the Rate of Change of Fuel Cost



For the solar power plants, the primary factor affecting the UAC is the capital costs of the plants. Therefore, analyses of the responsiveness of the UACs to changes in the capital costs of the plants is shown in Figure 5. If everything except the capital plant and storage costs is held constant, then capital costs for the solar power plants of approximately $45 to $47 million are required for the solar power plants and fossil fuel power plant to have similar UAC's. Significant changes in the probabilities affecting the various expected values would be required before they would have any real impact on the UAC of either type system. For the example contained herein, the effects of the different expected values were not required to make solar power plant number one economically attractive, while the effects of the expected values on the UAC's of the other two power plants had no significant impact on the overall UAC's. With greater probabilities of events, the expected values could become significant for analyses of other systems and locations.

Figure 5 Solar Power Plant
Capital Cost Change



CHAPTER 6

SUMMARY

A system for comparing the economic and strategic costs of fossil fuel and solar power plants was developed to evaluate the economic feasibility of utilizing solar power at remote military sites. This system utilizes the time value of money and inflation effects to provide a common basis of comparison for the alternative power sources. The equations developed can be easily modified to accommodate other cost factors, or nonuniform rates of change in cost factors. While the equations developed for solar power are primarily oriented towards solar thermal and photovoltaic power plants, they can be adapted to other "solar" power system types. Advances in system design, reductions in components costs, and reductions in energy storage costs coupled with rising fossil fuel costs will make solar power the economic choice for many remote locations which are removed from large centralized power plants. The examples showed that, for the costs and assumptions used, solar power could be economically competitive for Ascension AAF. The economic feasibility is highly dependent on the cost factors used for the solar power plant, therefore, any decision to implement solar power must involve cost analyses of a solar power plant optimized and designed for the site being considered and not the cost

factors contained in the examples. The expected values must be based on actual scenarios used by the Air Force for planning and on the appropriate cost factors.

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APPENDIX A

EXPECTED VALUES

The expected value of a discrete variable is obtained by multiplying the value of each event if it occurs by the probability of that event occurring and summing the results. For example, the expected value of the cost of security would be equal to the probability that security will be required times the cost of providing security per delivery, plus the probability that security will not be required times the cost if security is not required. This will give the expected value per delivery, and can be multiplied by the number of deliveries in the year to get the expected value for the year. For the purpose of this paper, it will be assumed that costs associated with probabilities of events occurring are each equal to zero or equal to the determined value for that cost factor, at any given time. In other words, at any time C_S is either zero or it is the full cost of providing security for a fuel delivery. Therefore, the expected value will be equal to the cost factor times the probability that the cost actually occurs.

Since the expected values of C_{MC}, C_{MI}, C_S, and C_{SD} will be used to determine costs, it is necessary to define the probabilities that will affect each of the cost factors. The basic theories of probability used in determination are contained in many statistics and probability texts (1,7). The probability of any one of the cost factors occurring will be a conditional probability of dependent events.

The probability of incurring a marginal cost for using fuel when demand exceeds supply is a function of the following dependent probabilities. First, the probability that a condition of excess demand will occur. Second, the probability that the condition of excess demand will last sufficiently long as to affect fuel delivery to the site. And third, the probability that deliveries of fuel to the site will be continued at a rate sufficient to maintain operational capabilities. (It is assumed that the marginal cost of using fuel during normal supply conditions is included in the price of the fuel.) As stated before, a condition of excess demand is a situation in which fuel is allocated on a basis other than price, such as rationing. The probability of incurring a marginal cost of fuel (P(MC)) is equal to the intersection of the probability of an excess demand condition (P(E)), the probability that the excess demand will last long enough to affect fuel delivery to the site ($P(T_e)$), and the probability that fuel deliveries to the site will continue at a rate sufficient to maintain operational capabilities ($P(D_e)$). Since this is a conditional probability of dependent variables, P(MC) is determined by;

$$P(MC) = P(E \mid T_e \cap D_e) = P(E) \times P(T_e \mid E) \times P(D_e \mid E \cap T_e)$$

For example, if $P(E) = 0.2$, $P(T_e) = 0.4$ given that the condition of excess demand has occurred, and $P(D_e) = 0.6$ given that the condition of excess demand has occurred and that it has lasted long enough to affect fuel deliveries, then

$$P(MC) = (0.2) \times (0.4) \times (0.6) = 0.048$$

Since the expected value of the marginal cost (E_{MC}) is equal to P(MC) times the marginal cost (C_{MC}), then for the example above, $E_{MC} = 0.048 \times C_{MC}$.

If sufficient fuel deliveries are not maintained to enable the site to be at full operational capabilities, then there will be a mission impact cost due to reduced or discontinued operational capabilities. The probability that there is a

mission impact cost (C_{MI}) is a function of P(E), P(T_e), and the probability that fuel deliveries will be reduced or discontinued (P(RD)). Since fuel deliveries can only be maintained, reduced, or discontinued, then P(RD) = 1 - P(D_e). Therefore:

$$P(MI) = = P(E) \times P(T_e|E) \times (1 - P(D_e | E \cap T_e))$$

The expected value of the mission impact cost (E_{MI}) is equal to the probability of a mission impact cost times the cost of a mission impact. E_{MI} = P(MI) x C_{MI}.

The probability that security (P(S)) will be required for fuel deliveries is a function of; First, the probability that hostile events will occur (P(H)) which would require that security be provided for any fuel deliveries. Second, the probability that the hostile events will last long enough to affect fuel deliveries to the site (P(T_h)), and third, the probability that the deliveries will be made given that security is required (P(D_s)). Therefore:

$$P(S) = P(H | T_h \cap D_s) = P(H) \times P(T_h|H) \times P(D_h | H \cap T_h)$$

The expected value of the cost of security (E_S) is equal to P(S) times C_S.

The probability that there will be fuel supply denial (P(FD)) due to hostilities is a function of: First, P(H); second, P(T_h); and third, the probability that the hostilities will cause fuel deliveries to be reduced or discontinued (P(SD)). Therefore,

$$P(FD) = P(H | T_h \cap SD) = P(H) \times P(T_h|H) \times P(SD | H \cap T_h)$$

The expected value of the cost of fuel supply denial (E_{SD}) is equal to P(SD) times C_{SD}.

If a cost factor is affected by more than one set of probabilities of events, then the actual expected value will be the summation of the expected value for each of the sets of probabilities. For example, the total expected value of

probabilities associated with a large scale conventional war, an expected value for the probabilities associated with a localized conflict, and an expected value for the probabilities associated with terrorist activities.

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